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13. ABSTRACT *(Maximum 200 words)*

USARIEM has developed a series of models which predict physiologic strain (body temperature, heart rate, sweating rate) and tolerance time to heat strain under a variety of conditions. These heat strain models have been incorporated into the P^2NBC^2 decision aid, JANUS, MERCURY and other military modeling efforts. The present study was conducted to fill-in information gaps for the database and provide validation of current algorithms. Specifically, this study reports physiologic information on the effects of: 1) light, moderate and hard exercise intensities; 2) MOPP 1 and MOPP 4; 3) desert (43°C (109°F), 20% rh) and tropic (35°C (95°F), 50% rh) climates. The physiologic information from these conditions were compared to values predicted by the ARIEM, HSDA and ARIEM-EXP (experimental) models. These experiments demonstrated: 1) harder work levels resulted in greater heat strain, which was more pronounced in MOPP 4 than in MOPP 1; 2) the energy cost of exercise and the heat strain was greater in MOPP 4 than MOPP 1 for the same task; 3) physiologic strain and tolerance times were similar during exercise in the two climates with matched WBGT temperatures; 4) the ARIEM and HSDA models were inaccurate in predicting the experimental core temperature responses, conservatively predicting core temperature responses, and over predicting tolerance time; 5) the ARIEM-EXP model accurately predicted core temperature responses, especially at moderate and hard exercise intensities, but it also over predicted tolerance time. These data indicate that the experimental model should replace the ARIEM and HSDA models to predict soldier responses in hot climates.

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EVALUATION OF USARIEM HEAT STRAIN MODEL: MOPP LEVEL, EXERCISE INTENSITY IN DESERT AND TROPIC CLIMATES

by

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Human subjects participated in these studies after giving their informed consent. Investigators adhered to AR 70-25 and USMRDC Regulation 70-25 on Use of Volunteers in Research.

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ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

USARIEM has developed a series of models which predict physiologic strain (body temperature, heart rate, sweating rate) and tolerance time to heat strain under a variety of conditions. These heat strain models have been incorporated into the P^2NBC^2 decision aid, JANUS, MERCURY and other military modeling efforts. The present study was conducted to fill-in information gaps for the database and provide validation of current algorithms. Specifically, this study reports physiologic information on the effects of: 1) light, moderate and hard exercise intensities; 2) MOPP 1 and MOPP 4; 3) desert (43°C (109°F), 20% rh) and tropic (35°C (95°F), 50% rh) climates. The physiologic information from these conditions were compared to values predicted by the ARIEM, HSDA and ARIEM-EXP (experimental) models.

These experiments demonstrated: 1) harder work levels resulted in greater heat strain, which was more pronounced in MOPP 4 than in MOPP 1; 2) the energy cost of exercise and the heat strain was greater in MOPP 4 than MOPP 1 for the same task; 3) physiologic strain and tolerance times were similar during exercise in the two climates with matched WBGT temperatures; 4) the ARIEM and HSDA models were inaccurate in predicting the experimental core temperature responses, conservatively predicting core temperature responses, and over predicting tolerance time; 5) the ARIEM-EXP model accurately predicted core temperature responses, especially at moderate and hard exercise intensities, but it also over predicted tolerance time. These data indicate that the experimental model should replace the ARIEM and HSDA models to predict soldier responses in hot climates.

INTRODUCTION

The U.S. Army Research Institute of Environmental Medicine (USARIEM) has developed a heat strain model using empirically derived equations to predict physiological responses of persons to heat exposure (6,7,17). This model is based on a prediction of a final equilibrium core temperature for any given set of environment, exercise and clothing parameters. Using interpolation algorithms, this model also predicts core temperature at any given time during exercise prior to reaching the equilibrium core temperature. In additional work funded by the U.S. Army Physiological and Psychological Effects of the NBC (nuclear, biological or chemical) Environment and Sustained Operations on Systems in Combat (P^2NBC^2) Program, the ARIEM model was expanded and adapted for use on personal computers. This work was accomplished by the Science Applications International Corporation (SAIC) and termed the P^2NBC^2 Heat Strain Decision Aid (HSDA).

Most recently a USARIEM effort has been undertaken to improve how closely the model predictions track minute by minute changes in measured core temperature. In a comparison of mathematical models predicting physiological responses to heat stress, Kraning showed that the HSDA systematically over predicted core temperatures relative to subject data in four out of five studies analyzed (12). In an initial attempt to reduce this over prediction of core temperature, a proportionality coefficient which slows the initial rapid rise in predicted core temperature response has been modified to create an experimental ARIEM model (ARIEM-EXP) (9).

The original ARIEM heat strain model inputs are environmental temperature, humidity, wind speed and solar load (1), metabolic rate during exercise, subjects' state of heat acclimation (8) and insulative level of clothing worn. The model then applies empirical equations to predict an average male soldier's rectal temperature (6) and sweating rate (20). The model uses these predicted physiological responses to calculate sustainable exercise/rest cycles, maximum single physical exercise time and water requirements for soldiers at various clothing, environment and exercise combinations (17). The predictions for exercise time are based on assumptions that exhaustion from heat strain occurs at specific body temperatures. The HSDA version of

established for research in humans in USARIEM M 70-68, AR 70-25 and USAMRDC 70-25 on the Use of Volunteers in Research.

EXPERIMENTAL DESIGN

Preliminary testing consisted of anthropometric measures [height, weight, estimate of per cent body fat by subcutaneous skinfolds thickness at four sites (3)], and maximal oxygen uptake, all of which provided descriptive data on the volunteers. The volunteers were familiarized with the NBC protective clothing and equipment and completed a ten day exercise-heat acclimation program before experiments began. After completing the exercise-heat acclimation program, the subjects completed twelve experiments. The subjects performed six experiments in each of the two climates. The order of the experiments was randomized relative to the appropriate comparisons.

Procedures/Measurements,

Maximal oxygen uptake ($\dot{V}O_2max$) was determined using a continuous effort treadmill test (2). Expired respiratory gases were collected and analyzed using a Sensormedics 2900 Metabolic Cart. Documented criteria (14,22) were used for determination of $\dot{V}O_2max$, or volunteers were stopped upon reaching a heart rate of 210 $b \cdot min^{-1}$ as established by the USARIEM Type Protocol. Nude weights were taken each morning before breakfast for five days to establish baseline weights (euhydrated) for the volunteers before they began exercising in a hot climate.

On one morning, subjects were fitted to the NBC protective clothing to be worn at the Mission Oriented Protective Posture (MOPP) level 4 during experimental tests. The clothing consisted of the battle dress overgarment (BDO) worn over t-shirt and shorts, socks, combat boots, green vinyl overboots (GVO), butyl hood, M25 protective mask, helmet, glove liners, and butyl gloves. The protective mask was modified for this study by having all the filters, the valves, and the voicemitter removed. These modifications minimized resistance to breathing, and mask dead space. Also, removing the voicemitter enabled better communications and increased subject safety during exercise in the heat.

In reviewing the biomedical aspects of protective masks, Muza (16) indicated that masks typically increase breathing resistance by four-fold over normal airway values, and that 10% of wearers generally experience breathing discomfort at minute ventilations ranging from 55 to 89 $l \cdot min^{-1}$. Removing the filters and voicemitter, minimized mask induced breathing difficulties as a criteria for terminating the experiments without interfering with the heat strain evaluation.

Once the subjects were fitted to the clothing and equipment, they took part in two mornings of familiarization in a climatic chamber at 18-20°C. The familiarization sessions included metabolic measurements (open circuit spirometry) at various treadmill speeds and grades, to determine each person's appropriate treadmill speeds and grades for the experimental tests. All subjects exercised at 2.0 mph, 0% grade for the light metabolic rate. Four subjects exercised at 3.0 mph, 0% grade and three subjects exercised at 3.0 mph, 2% grade for the moderate metabolic rate. The same four subjects exercised at 3.5 mph, 2% grade, and three subjects exercised at 3.5 mph, 5% grade for the high metabolic rate.

The subjects then participated in the ten day, exercise-heat acclimation program. Acclimation consisted of treadmill walking at 1.56 $m \cdot sec^{-1}$ on a 4% grade for 120 consecutive minutes. Environmental conditions during heat acclimation were 43.0°C T_{db}, 15.0°C T_{dp}, 20% rh and wind speed 1.1 $m \cdot sec^{-1}$. During acclimation, subjects wore shorts and athletic shoes or combat boots. They were instrumented for the monitoring of heart rate (HR) and core temperature (T_{re}). They wore the altered M25 protective masks for progressively longer periods of time on each acclimation day (from 10 to 60 minutes) to allow familiarization with wearing the protective mask for prolonged periods. Subjects were encouraged to drink water to maintain euhydration throughout each acclimation session. Pre-exercise nude weights were charted each day to assure that subjects did not undergo progressive dehydration. As an added precaution, each day before being released subjects were required to drink sufficient fruit juice or water to return their weight to the pre-determined baseline. This practice was continued throughout all experiments.

After completing the exercise-heat acclimation program, the subjects completed twelve experiments. Experiments were conducted in two environments: a desert climate (43°C T_{db}, 15°C T_{dp}, 12.8 Torr P_w, 20% rh, 30°C WBGT) and a tropic climate (35°C T_{db}, 23°C T_{dp}, 20.9 Torr P_w, 50% rh, 29°C WBGT). Wind speed was 2.2 $m \bullet s^{-1}$. The desert climate provided potential for greater evaporative cooling, while the tropic climate provided some potential for greater radiative and convective cooling even with matching WBGT's. In each experiment, the subjects attempted 180 minute treadmill walks at each of the three exercise intensities and in each of the two uniform configurations. Any given experiment was terminated at 180 minutes of exercise, predetermined core temperature endpoint (T_{re}=40°C) or heart rate (95% maximal heart rate) endpoint criteria. Experiments were also terminated whenever a subject exhibited the symptoms or signs of an impending heat injury, volitional termination or at the discretion of the medical monitor or investigator.

Table 1 shows the climate, uniform and metabolic rate for each experiment. Because of technical problems controlling the climatic chamber, all experiments in the desert condition were conducted prior to the tropic experiments. The subjects performed the experiments within each climate in a counterbalanced order to avoid an order effect on results. Three experiments in each climate (light, moderate and hard exercise intensities) were conducted in clothing configurations (MOPP) designed for a potential chemical threat (MOPP 1; battle dress overgarment (BDO), t-shirt, socks, boots, helmet) and three were conducted in clothing configurations designed for an imminent chemical threat (MOPP 4; all clothing and equipment worn and buttoned up). Each experiment consisted of the subjects attempting 180 minutes of continuous treadmill walking at light, moderate or hard exercise intensities. On each experimental test day, the subjects received 300 ml of water to drink immediately after obtaining the nude weight at arrival. The subjects were then given 300 ml of water to drink every 20 minutes while on the treadmill. Experiments were conducted in the morning with approximately 45 hours between tests to allow recovery of the subjects.

Table 1. Climate, uniform and metabolic rate configurations for each experiment.

DESERT 43°C, 20% rh	MOPP 1 250 W LIGHT	MOPP 4 250 W LIGHT	MOPP 1 425 W MOD.	MOPP 4 425 W MOD.	MOPP 1 600 W HARD	MOPP 4 600 W HARD
TROPIC 35°C, 50% rh	MOPP 1 250 W LIGHT	MOPP 4 250 W LIGHT	MOPP 1 425 W MOD.	MOPP 4 425 W MOD.	MOPP 1 600 W HARD	MOPP 4 600 W HARD

During all tests, T_{re} was measured by a flexible thermistor probe (YSI) inserted to a depth approximately 10 cm beyond the anal sphincter. During the experiments, skin temperature (T_{sk}) was measured with a four site skin thermocouple harness (chest, arm, thigh, calf). Mean weighted skin temperature ($\bar{T}_{sk}$) was calculated using the weighting system of 0.3 chest, 0.3 arm, 0.2 thigh, and 0.2 calf (18). T_{re}, T_{sk} and $\bar{T}_{sk}$ were obtained by a computerized data collection system. Heart rate was obtained from an electrocardiogram (chest electrodes, CM5 placement), displayed continuously on an oscilloscope cardiotachometer unit. Metabolic rate by open circuit spirometry were measured during the familiarization sessions, and on all experimental test days. Each day, expired air was collected in 150 liter Douglas bags for two minutes after the first 15 minutes of exercise. The ventilatory volume was measured in a Tissot gasometer, oxygen concentration was measured using an Applied Electrochemistry S 3-A electrochemical oxygen analyzer, and carbon dioxide concentration was measured using a Beckman LB-2 infrared carbon dioxide analyzer. These measured values were used to calculate metabolic rate during exercise.

Statistical Analyses

Statistical differences were tested at the $p<0.05$ level. Data are reported as the mean (± standard deviation). Multifactorial analyses of variance with repeated measures on the independent variables of exercise intensity, clothing configuration, climate and time, were used to analyze the dependent variables of T_{re} and $\bar{T}_{sk}$ at 15 minute intervals and HR at 10 minute intervals throughout the experiments. Each analysis was conducted through the final time with data for all subjects for the set of conditions being analyzed. Analyses of variance were also conducted for the discrete dependent variable of tolerance time for each experiment. When significant

differences were found, Tukey's test of critical difference was used for post hoc analyses.

The root mean squared deviation (RMSD) as proposed by Haslam and Parsons (10) was used for comparative statistical evaluation between the mathematical models and the subject test results. The RMSD is a summary statistic which provides numerical values for an average difference between observed and predicted measurements collected across time, and is compared with the average standard deviation of the subject data.

The RMSD is defined as:

$$RMSD = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n} d_i^2\right)}$$

d_i = difference between observed and predicted at each time point on a minute by minute basis

n = number of comparison time points

RESULTS

Completion of the heat acclimation program resulted in decreased heart rate (20 b•min $^{-1}$) and decreased core temperature (0.47°C) at a given experimental time in the hot climate. In general, the physiologic responses of the subjects in this study were expected for the given experimental conditions. Harder exercise resulted in greater heat strain, and the indices of heat strain (core temperature, skin temperature, heart rate) were more pronounced in MOPP 4 than MOPP 1. Also, the metabolic demand of a given exercise condition was greater in MOPP 4 than MOPP 1. Finally, at each MOPP level and at equivalent exercise intensities, the physiologic strain and tolerance

times were similar for the two climates with matched WBGT. Summaries of statistical comparisons for all variables are presented in Appendix B. Graphs of physiologic data are presented in Appendix C as Figures 1C through 6C.

Metabolic Rate

In the desert climate at MOPP 1, the mean (±SD) metabolic rate was 284±34 W during light exercise, 414±32 W during moderate exercise and 582±53 W during hard exercise (Figure 1). In the desert climate at MOPP 4, the mean (±SD) metabolic rate was 315±41 W during light exercise, 446±52 W during moderate exercise and 620±56 W during hard exercise (Figure 1). In the tropic climate at MOPP 1, the mean (±SD) metabolic rate was 279±37 W during light exercise, 401±43 W during moderate exercise and 572±58 W during hard exercise (Figure 2). In the tropic climate at MOPP 4, the mean (±SD) metabolic rate was 293±35 W during light exercise, 442±51 W during moderate exercise and 606±70 W during hard exercise (Figure 2).

Tolerance Time

In the desert climate at MOPP 1, the mean (±SD) tolerance time was 180±0 minutes (the controlled endpoint) during light exercise, 168±16 minutes during moderate exercise and 99±28 minutes during hard exercise (Figure 3). In the desert climate at MOPP 4, the mean (±SD) tolerance time was 122±43 minutes during light exercise, 69±14 minutes during moderate exercise and 46±11 minutes during hard exercise (Figure 3). In the tropic climate at MOPP 1, the mean (±SD) tolerance time was 170±28 minutes during light exercise, 159±37 minutes during moderate exercise and 101±34 minutes during hard exercise (Figure 4). In the tropic climate at MOPP 4, the mean (±SD) tolerance time was 158±38 minutes during light exercise, 82±20 minutes during moderate exercise and 48±11 minutes during hard exercise (Figure 4).

Core Temperature Comparison with Models

The RMSD's for the HSDA, ARIEM and ARIEM-EXP heat strain models are listed for each of the 12 experiments in Table 2. Table 2 also provides the subjects' average standard deviation from mean core temperature over the time course of each of the 12 experiments. For the HSDA model, the RMSD's ranged from 1.3 to 5.6 times greater than subject average mean standard deviation, and exceeded two times greater in 10

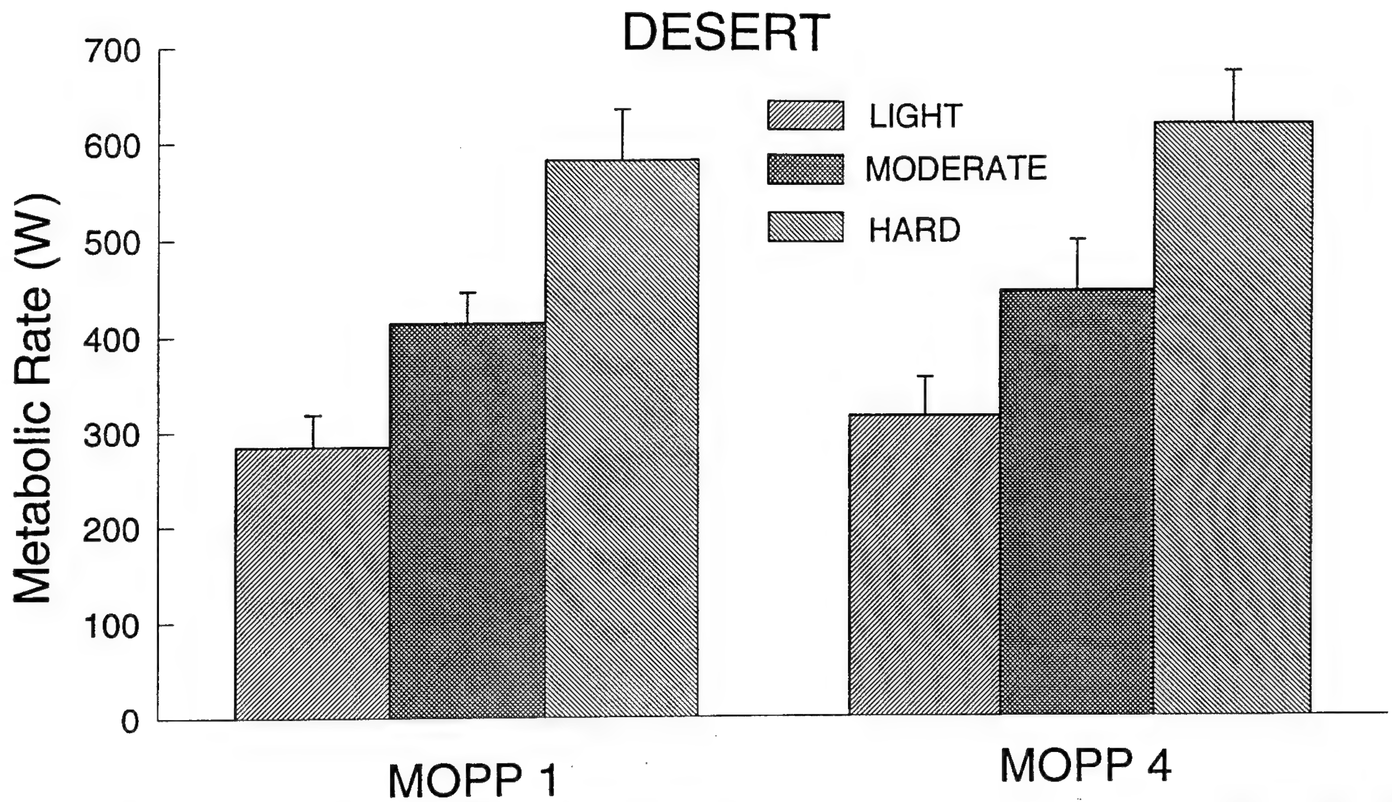

Figure 1. The mean ±SD metabolic rates of the subjects during all experiments in the des climate in both MOPP 1 and MOPP 4.

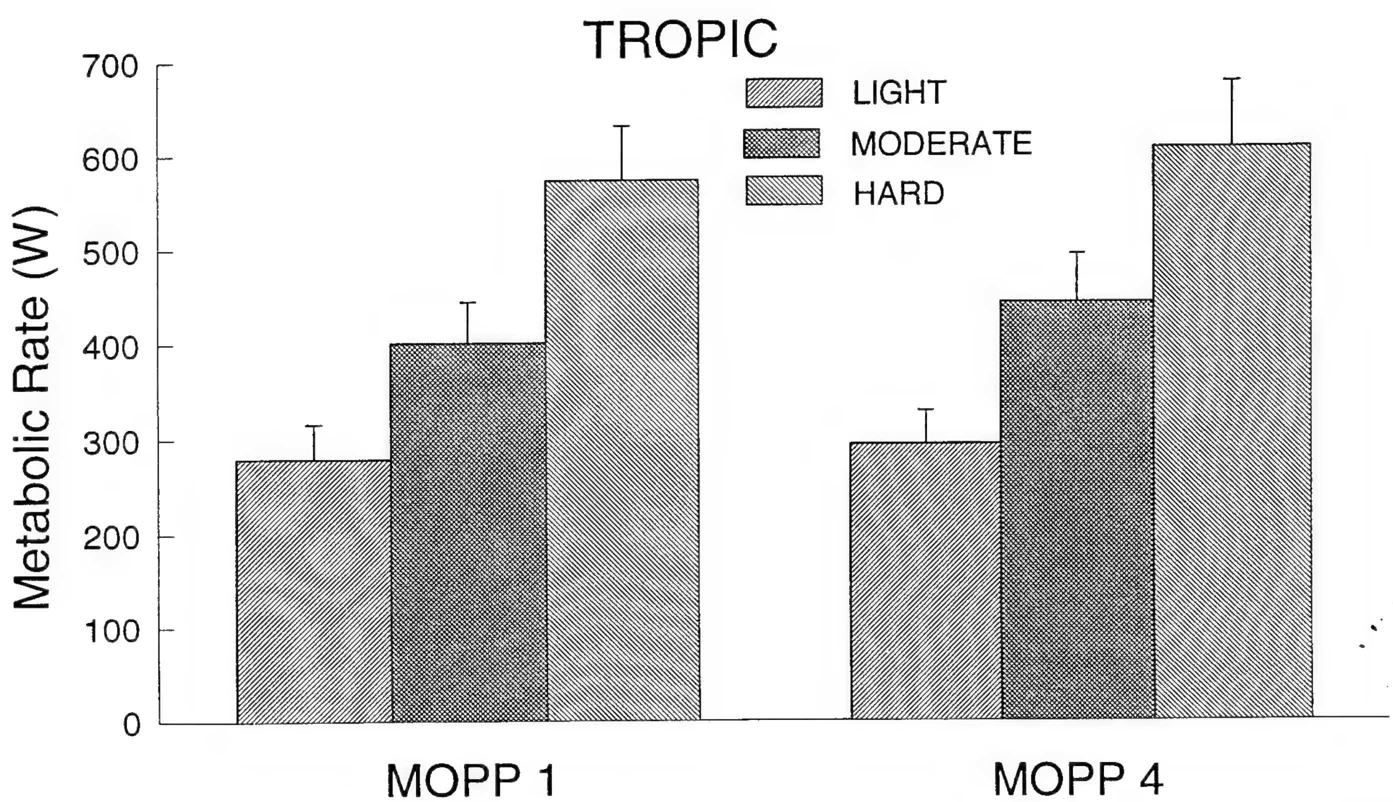

Figure 2. The mean ±SD metabolic rates of the subjects during all experiments in the tropi climate in both MOPP 1 and MOPP 4.

of 12 conditions. For the ARIEM model, the RMSD's ranged from 1.6 to 5.4 times greater than the subject mean average standard deviation, and exceeded two times greater in 11 of 12 conditions. The three experiments with the most favorable comparisons between observed data and the predicted core temperature responses with the HSDA and ARIEM models all occurred in MOPP 1; at hard exercise in the desert and tropic climates and moderate exercise in the desert climate. In both hard exercise comparisons, the HSDA and ARIEM models are reasonably accurate partly because there is more variability as evidenced by the subjects' standard deviations. For the ARIEM-EXP model, the RMSD's ranged from 0.3 to 2.5 times the average subject standard deviation from mean core temperature in all of the experimental conditions. In 5 of the 12 experimental conditions, the RMSD's for the ARIEM-EXP model were greater than two times the subject standard deviation from mean core temperature. Four of these five conditions were the four light exercise intensity experiments. The fifth condition with an ARIEM-EXP model RMSD greater than twice the average subject standard deviation was at the moderate exercise intensity in MOPP 1 in the tropic climate.

Graphic representation of the subjects' mean core temperature response and the prediction models' estimates are presented in Figures 5-8. The graphs all show that whenever the subjects were performing light exercise, none of the three models accurately predicted temperatures. During light work, all the models show a steeper increase during the early portion of the exercise, and level off at temperatures higher than ever achieved by the exercising subjects. This same pattern is also apparent for the HSDA and ARIEM models when compared with mean subject data in all testing conditions (Figures 5-8). However, the ARIEM-EXP accurately predicts the mean core temperature curve in all experiments except those at the light metabolic rate.

The models' predictions of time to reach a core temperature of 40°C (the models' assumed 50% heat casualty rate) and the observed mean exercise tolerance times are presented in Table 3. The HSDA model predicted tolerance times of over 300 minutes (the default maximal time) in eight of the 12 experimental conditions. The ARIEM model predicted tolerance times of over 300 minutes in six of the 12 experimental conditions. The ARIEM-EXP model predicted tolerance times of over 300 minutes in

eight of the twelve experimental conditions. The actual exercise tolerance results show that the subjects achieved the experimental maximal time of 180 minutes in only one experimental condition. This was in the desert climate at light exercise in MOPP 1.

In examining the individual tolerance times of the subjects, there were no cases of exhaustion from heat strain in MOPP 1 during the 14 light exercise intensity experiments. There were 19 instances of exhaustion from heat strain out of the remaining 28 total individual experiments in MOPP 1 at the moderate and hard exercise intensities. These 19 instances account for 68% of the total moderate and hard exercise experiments in MOPP 1. In these 19 instances, the 50th percentile core temperature of the subjects was 38.7°C. There were 35 instances of exhaustion from heat strain across all three exercise intensities out of the 42 total individual experiments in MOPP 4. These 35 instances account for 71% of the total experiments in MOPP 4. In these 35 instances, the 50th percentile core temperature of the subjects was 38.5°C.

Table 2. The calculated root mean squared deviation values for the HSDA, ARIEM and ARIEM-EXP models and the average mean standard deviation for rectal temperature values across time for each experiment.

	LIGHT MOPP 1	LIGHT MOPP 4	MOD. MOPP 1	MOD. MOPP 4	HARD MOPP 1	HARD MOPP 4
DESERT						
HSDA	0.53	0.88	0.53	0.87	0.47	1.05
ARIEM	0.70	0.96	0.68	0.81	0.55	0.99
ARIEM-EXP	0.37	0.44	0.21	0.14	0.25	0.07
AVERAGE SD	0.16	0.19	0.29	0.21	0.34	0.24
TROPIC						
HSDA	0.53	0.84	0.68	0.90	0.70	0.83
ARIEM	0.72	0.98	0.97	0.87	0.82	0.78
ARIEM-EXP	0.39	0.58	0.41	0.21	0.20	0.11
AVERAGE SD	0.17	0.23	0.19	0.16	0.39	0.26

Table 3. The calculated time in minutes to reach a core temperature of 40°C for the HSDA, ARIEM and ARIEM-EXP models and the observed mean ± standard deviation subject values for tolerance time in each experiment.

	LIGHT MOPP 1	LIGHT MOPP 4	MOD. MOPP 1	MOD. MOPP 4	HARD MOPP 1	HARD MOPP 4
DESERT						
HSDA	300*	300*	300*	95	300*	51
ARIEM	300*	300*	300*	85	131	51
ARIEM-EXP	300*	300*	300*	146	300*	90
AVERAGE $\bar{X}$±SD	180*	122 ±43	168 ±16	69 ±14	99 ±28	46 ±11
TROPIC						
HSDA	300*	300*	300*	113	300*	57
ARIEM	300*	300*	300*	94	123	56
ARIEM-EXP	300*	300*	300*	166	300*	96
AVERAGE $\bar{X}$±SD	170 ±28	158 ±38	159 ±37	82 ±20	101 ±34	48 ±11

* maximum time generated by model or maximum time of experiment.

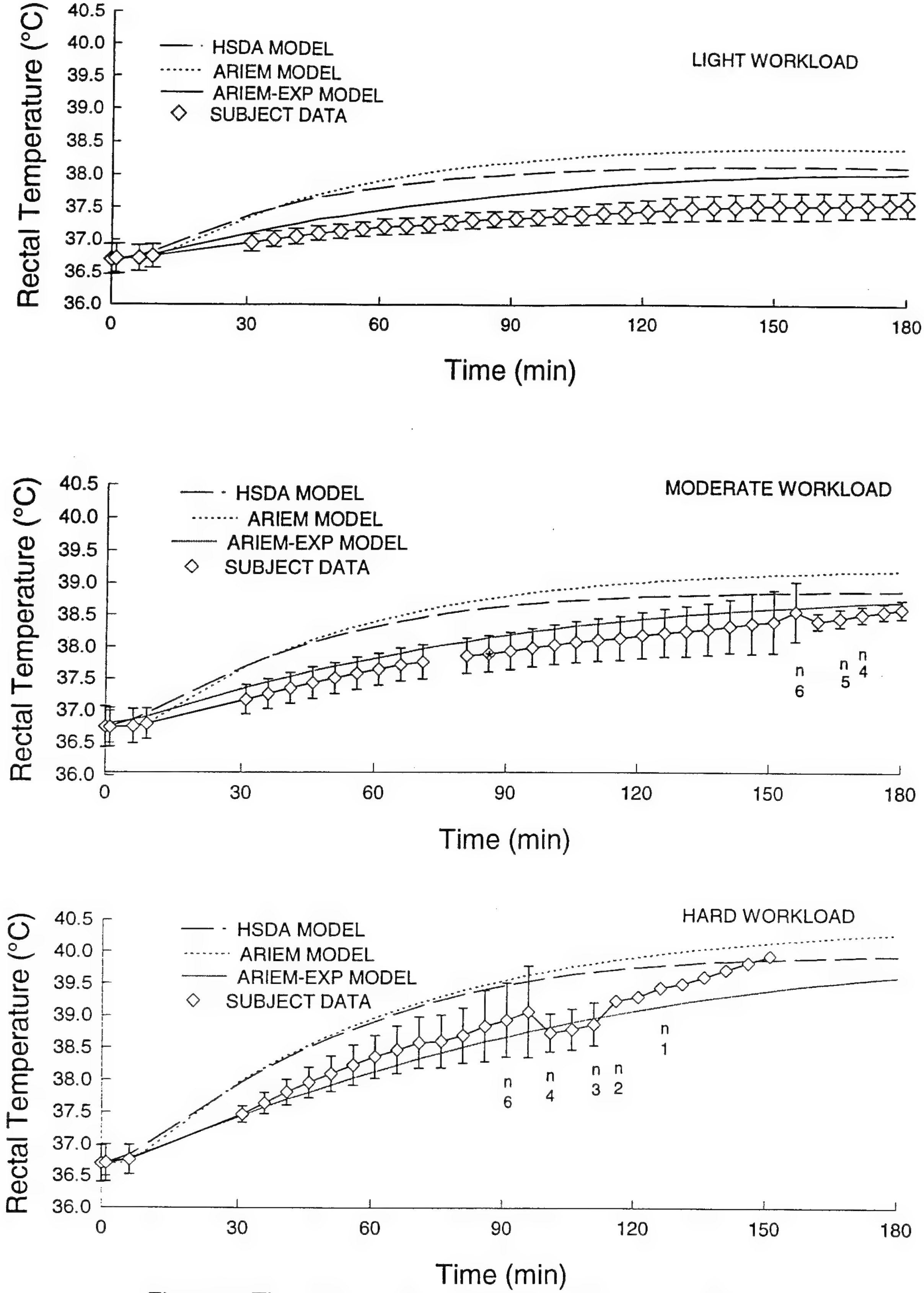

Figure 5. The mean ± core temperatures of seven subjects and three prediction model estimates during light (top), moderate (center), and hard workloads in the desert climate in MOPP 1. n= remaining subjects; * missing data point.

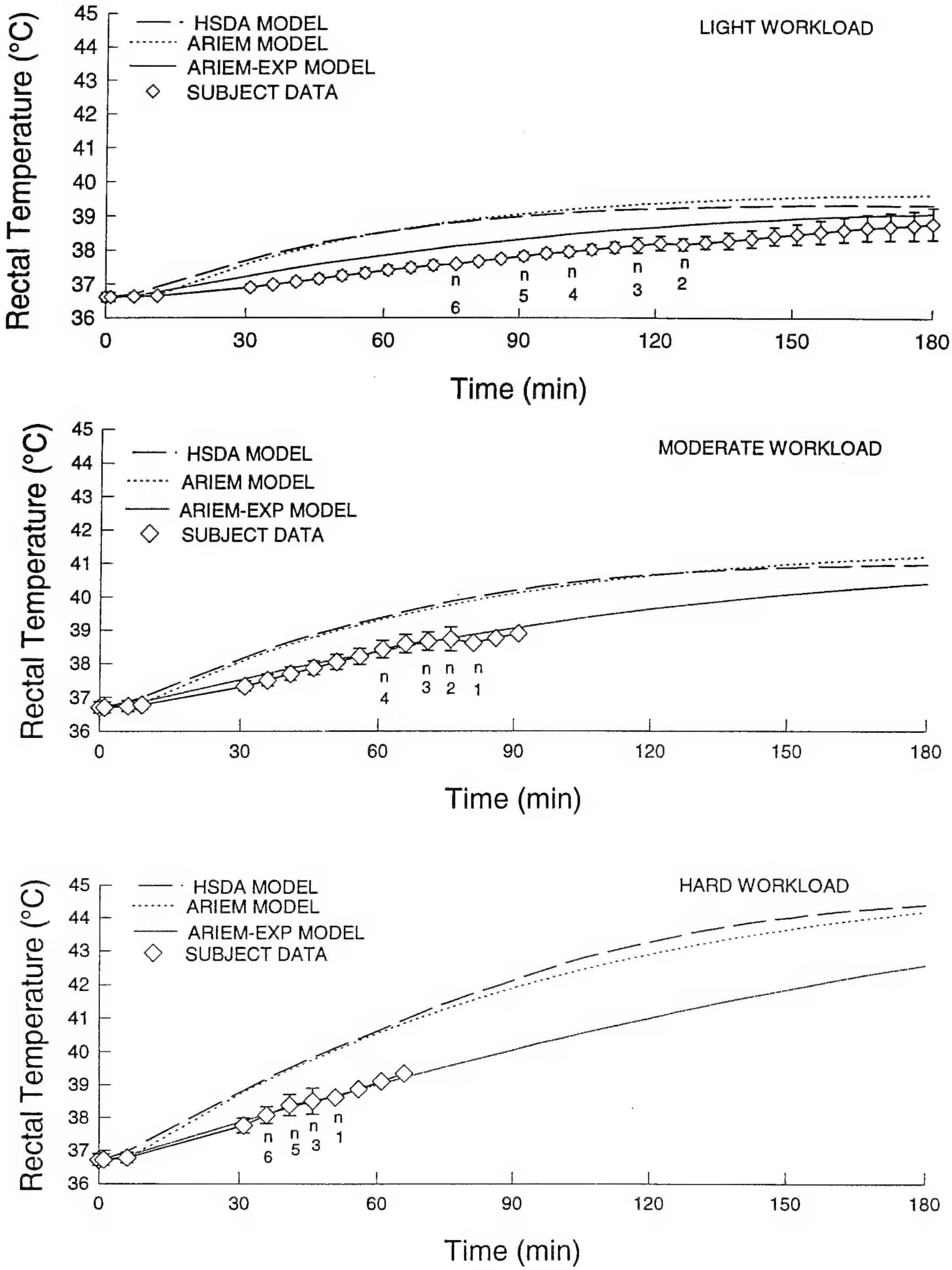

Figure 6. The mean ± core temperatures of seven subjects and three prediction model estimates during light (top), moderate (center), and hard workloads in the desert climate in MOPP 4. n= remaining subjects

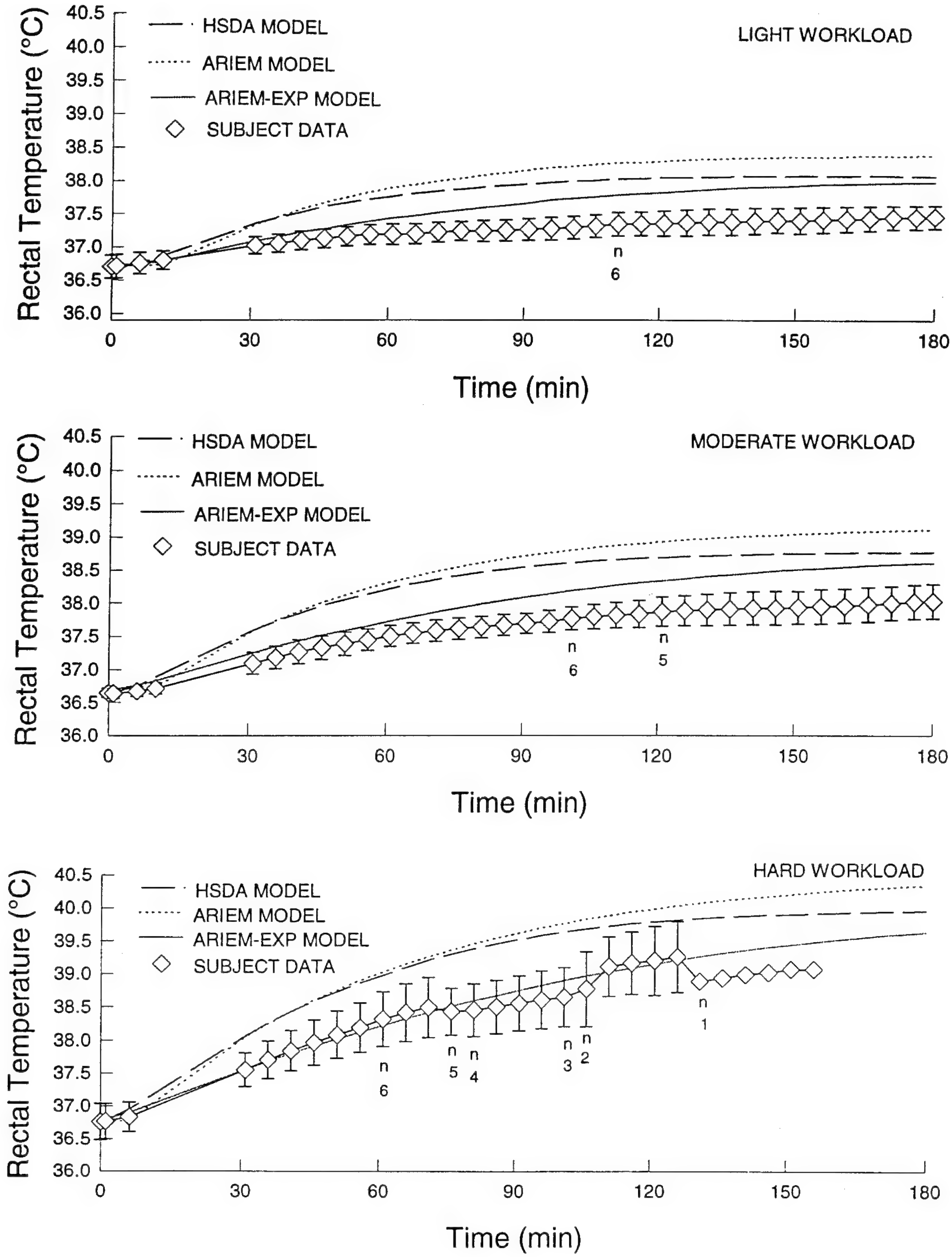

Figure 7. The mean ± core temperatures of seven subjects and three prediction model estimates during light (top), moderate (center), and hard workloads in the tropic climate in MOPP 1. n= remaining subjects

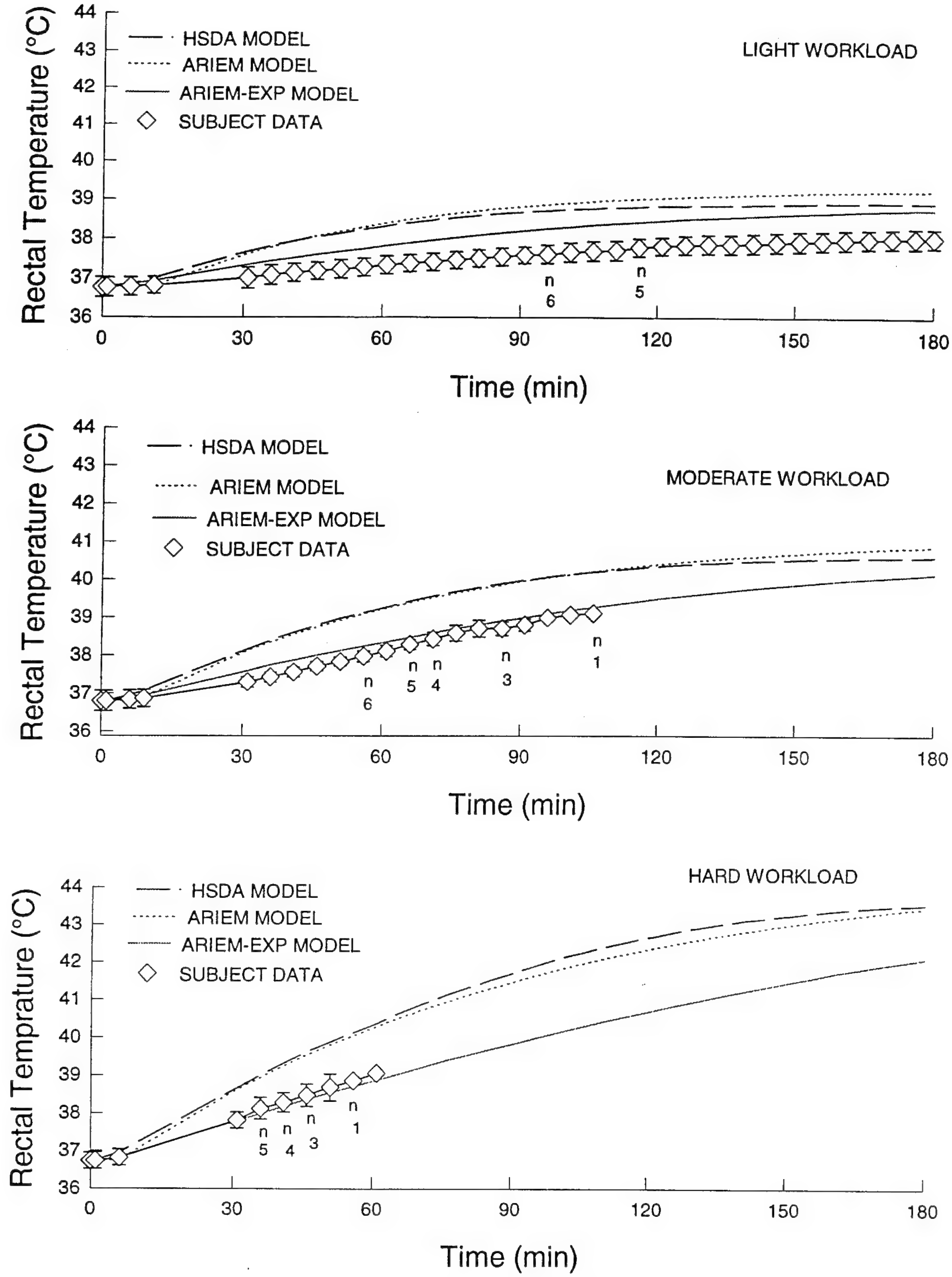

Figure 8. The mean ± core temperatures of seven subjects and three prediction model estimates during light (top), moderate (center), and hard workloads in the tropic climate in MOPP 4. n= remaining subjects

PHYSIOLOGIC RESPONSES

Core Temperatures

In the desert climate in MOPP 1, the mean (±SD) T_{re}'s were 37.2±0.1°C during light exercise, 37.6±0.3°C during moderate exercise and 38.3±0.3°C during hard exercise by 60 minutes (Appendix C, Figure 1C). In the desert climate in MOPP 4, mean (±SD) T_{re}'s were 36.9±0.1°C during light exercise, 37.3±0.1°C during moderate exercise and 37.7±0.2°C during hard exercise by 30 minutes (Appendix C, Figure 2C). In the tropic climate in MOPP 1, the mean (±SD) T_{re}'s were 37.2±0.2°C during light exercise, 37.5±0.2°C during moderate exercise and 38.3±0.4°C during hard exercise by 60 minutes (Appendix C, Figure 1C). In the tropic climate in MOPP 4, the mean (±SD) T_{re}'s were 37.0±0.3°C during light exercise, 37.3±0.1°C during moderate exercise and 37.8±0.2°C during hard exercise by 30 minutes (Appendix C, Figure 2C).

Mean Weighted Skin Temperatures

In the desert climate in MOPP 1, the mean (±SD) $\bar{T}_{sk}$'s were 35.6±0.2°C during light exercise, 36.0±0.3°C during moderate exercise, and 36.4±0.4°C during hard exercise by 60 minutes (Appendix C, Figure 3C). In the desert climate in MOPP 4, the mean (±SD) $\bar{T}_{sk}$'s were 35.7±0.2°C during light exercise, 36.3±0.3°C during moderate exercise and 36.8±0.3°C during hard exercise by 30 minutes (Appendix C, Figure 4C). In the tropic climate in MOPP 1, the mean (±SD) $\bar{T}_{sk}$'s were 34.9±0.3°C during light exercise, 35.6±0.1°C during moderate exercise and 36.3±0.4°C during hard exercise by 60 minutes (Appendix C, Figure 3C). In the tropic climate in MOPP 4, the mean (±SD) $\bar{T}_{sk}$'s were 35.3±0.2°C during light exercise, 35.8±0.2°C during moderate exercise and 36.5±0.3°C during hard exercise by 30 minutes (Appendix C, Figure 4C).

Heart Rate

In the desert climate in MOPP 1, the mean (±SD) HR's were 103±5 $b{\bullet}min^{-1}$ during light exercise, 129±13 $b{\bullet}min^{-1}$ during moderate exercise and 157±17 $b{\bullet}min^{-1}$ during hard exercise by 60 minutes (Appendix C, Figure 5C). In the desert climate in MOPP 4, the mean (±SD) HR's were 109±7 $b{\bullet}min^{-1}$ during light exercise, 134±11 $b{\bullet}min^{-1}$ during moderate exercise and 160±17 $b{\bullet}min^{-1}$ during hard exercise by 30 minutes (Appendix C, Figure 6C). In the tropic climate in MOPP 1, the mean (±SD) HR's were 96±6 $b{\bullet}min^{-1}$

during light exercise, 120±9 b•min^{-1} during moderate exercise and 149±18 b•min^{-1} during hard exercise by 60 minutes (Appendix C, Figure 5C). In the tropic climate in MOPP 4, the mean (±SD) HR's were 107±13 b•min^{-1} during light exercise, 129±12 b•min^{-1} during moderate exercise and 160±18 b•min^{-1} during hard exercise by 30 minutes (Appendix C, Figure 6C).

DISCUSSION

The root mean squared deviation (RMSD) analyses were used to compare the observed core temperatures with the predicted values generated by the HSDA, ARIEM and the ARIEM-EXP models. Primarily the RMSD of the HSDA and ARIEM models were greater than two calculated standard deviations from the experimental data. This would indicate that the models' predictions fall outside the response of 95% of an average population. Additionally, observation of the graphs shown in Figures 5-8 show that the HSDA and USARIEM models routinely over-predicted the subjects' temperatures at any given time, consistently providing conservative heat strain evaluations for a given heat stress situation.

The ARIEM-EXP model attempts to correct some deficiencies in the original ARIEM model. The ARIEM-EXP model, as modified by Gonzalez et al. (9), uses a proportionality control coefficient to buffer the abrupt rise of rectal temperature which is integral in the equations used in the HSDA and USARIEM models. This change does not alter the final steady state equilibrium core temperature as calculated by the original Givoni and Goldman equations (6,8), but simply reduces the rate of rise in the early portion of the curve. This in turn decreases RMSDs which are closer to the standard deviation. In six of 12 comparisons (using the ARIEM-EXP model), the RMSD's are within one standard deviation of collected data. The RMSD is slightly greater than one SD in one other comparison and just over two standard deviations in the other five instances using the ARIEM-EXP model. With both the HSDA and ARIEM models, the RMSD's are over three times greater than the measured standard deviations in 9 of 12 comparisons, and in no comparison is the RMSD smaller than the standard deviation over the course of an experiment.

The ARIEM-EXP model shows the greatest variation from the measured data during light exercise in both climates and both uniform configurations, and during moderate exercise in the tropic climate in MOPP 1. The light exercise conditions created the lowest amount of heat stress, and the greatest lag before onset of significant heat storage. Even with the altered proportionality control coefficient included in the equations, the predicted rise in core temperature was more rapid than the observed rise in core temperature. The MOPP 1 condition in the tropic climate at moderate exercise, caused a more gradual increase in core temperature relative even to the ARIEM-EXP model with the altered proportionality control. In the desert climate in MOPP 1 at moderate exercise, a core temperature plateau was not achieved due to the higher ambient and skin temperatures, and less ability to dissipate heat. Because of this, the subjects data and ARIEM-EXP model tracked more closely than in the tropic climate with the same clothing and exercise intensity.

The HSDA and ARIEM models consistently predicted higher T_{re} values than those observed during a given heat stress situation as a result of rapid, early increases in core temperature. The ARIEM-EXP model was much more accurate predicting T_{re} values at moderate and hard exercise intensities in extreme environments. In addition, a basic premise of the models is that the maximum allowed core temperature criterion of 40°C used for this study would result in a 50% casualty rate among the subjects. The data from this study does not support this assumption. As we have stated, in this study 68% of the moderate and hard exercise experiments in MOPP 1 resulted in exhaustion from heat strain (all at temperatures lower than 40°C) with the 50th percentile core temperature of these subjects at 38.7°C, and 71% of the total experiments in MOPP 4 resulted in exhaustion from heat strain (all at temperatures lower than 40°C) with the 50th percentile core temperature of these subjects at 38.5°C. These numbers are in good confirmation with the findings of Sawka et al. (19).

The heat strain tolerance curves reported by Sawka et al. (19) showed that 50% of euhydrated subjects were exhausted from heat strain at a core temperature of 38.8°C, and 50% of the hypohydrated subjects were exhausted from heat strain at a core temperature of 38.5°C. Although the mechanisms to reach exhaustion from heat strain may not be identical between a hypohydrated individual dressed in shorts and a

hydrated individual dressed in MOPP 4, it is interesting to note that the 50th percentile for both groups was identical. Also, the 50th percentile temperatures for exhaustion for euhydrated individuals dressed in shorts and euhydrated individuals dressed in MOPP 1 were within 0.1°C of each other. It is of interest that these temperatures for exhaustion from heat strain are well below 40°C.

The results of our validation study differ from reported results showing closer confirmation between experimental data and ARIEM model predictions (6,13,17). One possible reason for the differences is alterations have been made in the equations as a result of findings made from copper manikin data using various wind speeds and advanced uniform configurations. These findings have resulted in altered CLO and I_m values from those used in earlier versions of the model (6). These alterations, which are different between even the HSDA and ARIEM models used in this research, affect how closely the models predict physiological responses. It is possible that while the altered CLO and I_m values more accurately describe the uniform systems, their overall impact is to make the model less accurate in tracking core temperature responses.

A second reason our tests differ from previous studies showing closer confirmation results from setting the initial core temperature of the model equal to the mean core temperature of the subjects for a given set of experiments. In the paper on prediction modeling by Pandolf et. al. (17), one figure shows observed and predicted rectal temperature responses from soldiers in three clothing ensembles during tests in Australia. The graphs on both U.S. and United Kingdom chemical protective clothing in the closed configuration, indicate that the modeling prediction started from a lower core temperature than the recorded subject data, and then proceeded to rise at a more rapid rate than the measured values. However, because the modeling values started at a lower core temperature they were still within one standard deviation of the observed data when the graphs were truncated at 25 minutes. Because our modeling data started at the same temperature as the mean subject core temperature, the rapid rise during the early portion of the experiments resulted in a larger difference between the observed data and modeling prediction during the first 25 minutes of data collection.

A third reason our test results differ from results showing closer confirmation involves a combination of differences between environmental conditions used and type of analysis chosen to validate the data. Research by McClellan et al. (13) was conducted on subjects in chemical protective clothing in environments of 18°C, 50% rh and 30°C, 50% rh. Mean core temperatures at the final tolerance time were compared with predicted core temperatures at same number of minutes of exercise. In analyzing the model at a single point in time, it is impossible to take into consideration changes between the model and observed data over the time course of an experiment as can be done by use of the RMSD analysis. Also, in the McClellan study the closest relationships between the model and observed data were in an environment and exercise condition where there was compensable heat stress (18°C, ~343 W), and also for the two heavy exercise conditions (18 and 30°C, ~650 W).

Not all previous evaluations of the USARIEM model indicated a close confirmation between the predicted and observed physiological responses to heat stress. In a paper by Haslam and Parsons evaluating computer models versus human responses (10), two examples of experimental data, one by Chappuis et al. and one by Henane et al., both show RMSD values using the ARIEM model which are much larger than the subject standard deviations. The study by Chappuis et al. examined subjects performing exercise on a cycle ergometer at 150 $W \cdot m^{-2}$ for 50 minutes, $W \cdot m^{-2}$ for 50 minutes and resting at 57 $W \cdot m^{-2}$ for 30 minutes in 20, 25 and 30°C environments. Core temperatures were measured using tympanic temperature. The RMSD calculations from this data were 6, 3.4 and 1.8 times greater than the observed average standard deviation at each of the increasing temperatures. Henane et al. examined subjects performing the same intensity of exercise on a cycle ergometer (output 50 W) for 60 minutes in a 35°C, 54% rh environment. The subjects each completed three experiments, once nude and in two different levels of chemical protective clothing. Core temperatures were measured using rectal temperature. The RMSD calculations from this data were 1.4, 1.8 and 2.6 times greater than the observed average standard deviation in the nude and increasingly more insulative protective equipment, respectively.

Further, Kraning's validation of three models (12) using RMSD comparisons against observed physiological responses from five sets of experiments, showed the RMSDs with the HSDA model to be much larger than the subjects standard deviation in four out of five sets of experiments. In two of the sets of experiments examined for validation of the models and conducted by Kraning, subjects performed treadmill walking in a 30°C, 25% rh environment, once in shorts and t-shirts and once in the BDO over the BDU in the MOPP 4 configuration. Core temperatures were measured using rectal temperatures. The RMSD calculations from these two sets of experiments were 2.3 and 3.3 times greater than the observed average standard deviation in the shorts and MOPP 4 configurations respectively.

Another set of experiments examined for validation of the models by Kraning was conducted by Gonzalez et al.. The subjects each completed 16 experiments dressed in shorts, exercising on a cycle ergometer at 28% of $\dot{V}O_2max$, in environments of varying temperature and humidity combinations. Core temperature was measured by esophageal temperature. The RMSD calculations from this data were 4.2 times greater than the observed average standard deviation from the experiments. In other experiments conducted by Gonzalez et al., the subjects performed 70 minutes of treadmill walking in a 35°C, 50% rh environment while wearing chemical protective clothing in the MOPP 4 configuration. Core temperatures were measured by rectal temperature. The RMSD calculations from this data were 3.6 times greater than the observed average standard deviation from the experiments.

The ARIEM and HSDA prediction models were originally developed to predict both the final equilibrium rectal temperature and the time to reach that temperature for steady state work in a given environment. Predicted core temperature curves from the start of exercise through the final equilibrium core temperature were also calculated from given inputs. The model has been revised and updated over time, and this process needs to continue, with some changes in the equations to represent the dynamic physiological changes in the body as it attempts to meet the demands of a given heat stress. Additionally, further consideration needs to be given to predicting what percentage of personnel will be lost to heat strain either as core temperature goes up or rate of heat storage increases during an exercise-heat stress (15).

It is recommended from the findings of this study, that: 1) the ARIEM-EXP currently be used for prediction modeling as it most closely represents physiological response; 2) the ARIEM-EXP be modified with an alternate proportionality coefficient for low metabolic cost exercise; 3) the ARIEM-EXP be modified with input from the heat strain curves such as from Sawka et al. (19) to better predict tolerance time; 4) additional models be examined such as those by Stolwijk (21), Gagge (4,5)and Kraning(11), which more carefully investigate the transient state of the body as it is affected by the environment, clothing and exercise.

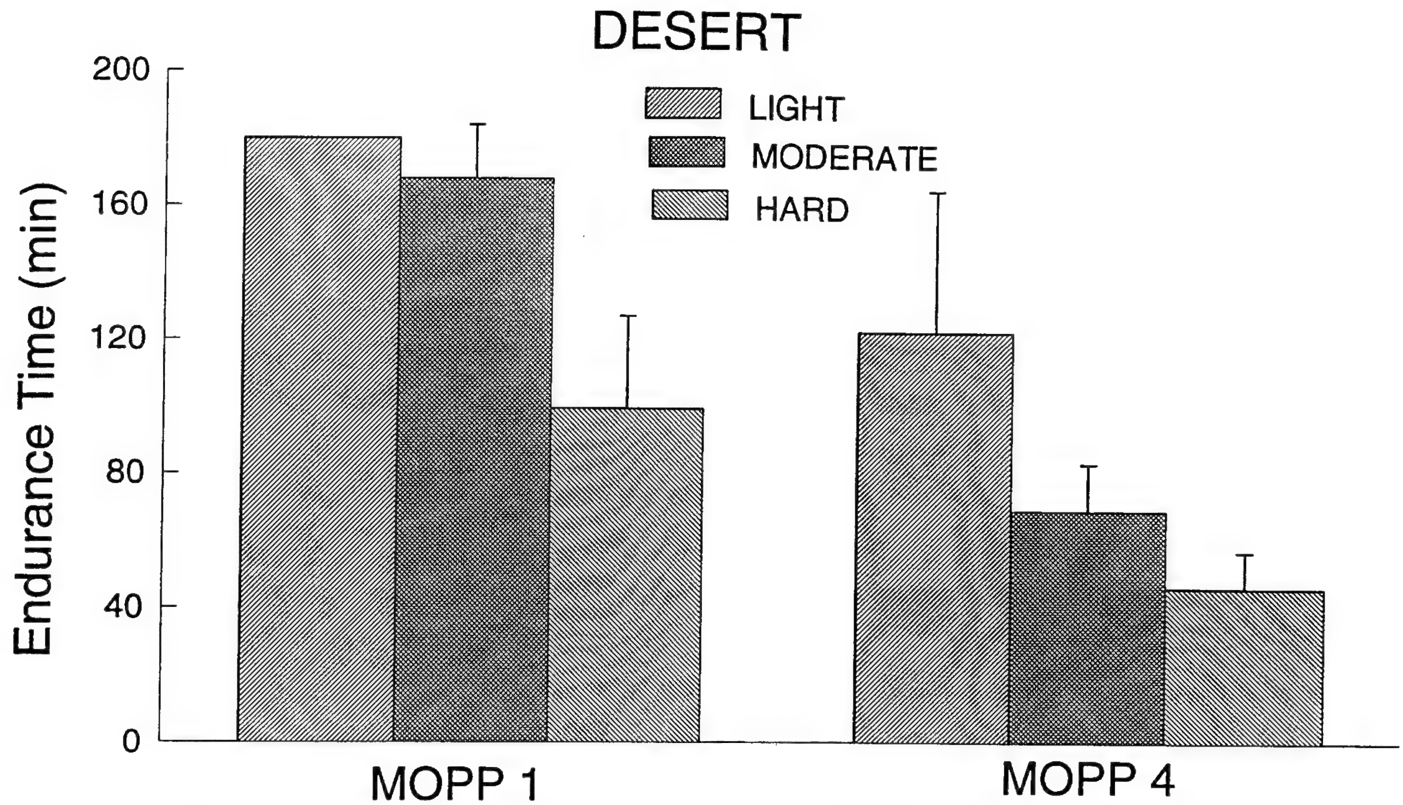

Figure 3. The mean ±SD endurance time of the subjects during all experiments in the desert climate in both MOPP 1 and MOPP 4.

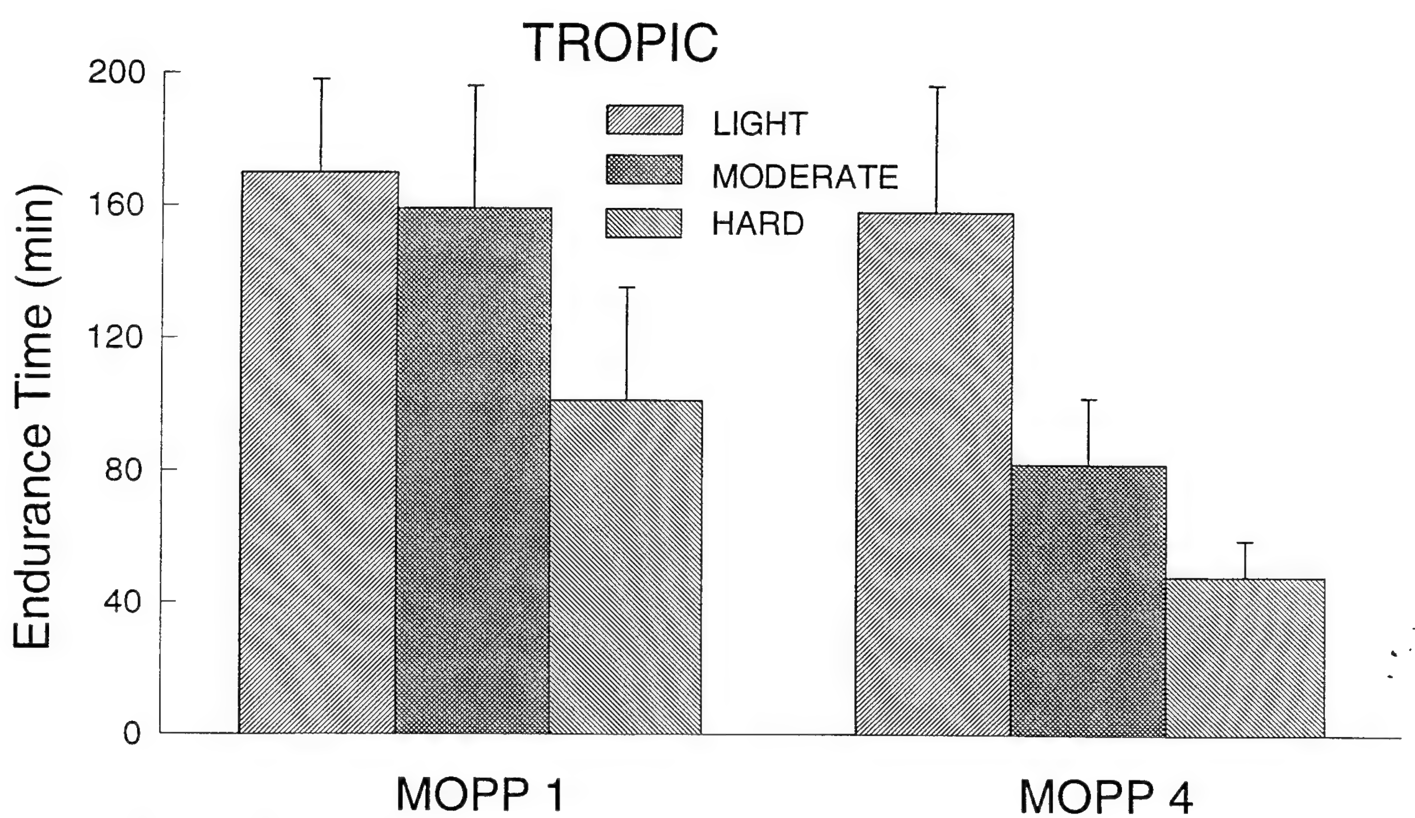

Figure 4. The mean ±SD endurance time of the subjects during all experiments in the tropic climate in both MOPP 1 and MOPP 4.

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APPENDIX A

SOLDIER PERFORMANCE DATABASE SUMMARY

STUDY #	# SUB	TEMP °C	%RH	WIND SPEED m/s	MET RATES
1	6	45 35	30 70	1.0	~4.5
2	4	30	25	0.2	a) 3.0 b) repeated 3,8, and 1
3	6	29.5 29.5 29.5	20 20 85	5.0 1.1 5.0	repeated: 3,1
4	12	18.3 32.2 32.2	70 20 80	1.1	repeated: 3,1
5	16	29.4	30	5.0	repeated: 3,1
6	18	35	20	2.2	repeated: 3,1
7	6	35.1 40.6	40 10	1.1	repeated: 1,4
8	14	31.7 35.0 42.8	80 50 20	1&5 1&5 1&5	~4
9	4	49	20	1.0	repeated: 1.8,3.1
10	8	36.6 38.8 35.7 35.3	33 57 66 91	--	by subject: driver 1.5 gunner 2.0 loader 3.6 commander 1.5
11	8	32.8	60	0.1	same as study #10

APPENDIX B

Summary Tables of Statistical Comparisons

The five Tables in Appendix B indicate anywhere significant differences occurred among exercise intensities, between MOPP levels or between climates in the physiologic measurements of metabolic rate, core temperature, mean skin temperature, heart rate and tolerance time.

METABOLIC RATE

Exercise Level	MOPP 1 L	MOPP 1 M	MOPP 1 H	MOPP 4 L	MOPP 4 M	MOPP 4 H
Desert	< M,H	< H	-	< M,H	< H	-
Tropic	< M,H	< H	-	< M,H	< H	-

MOPP Level	MOPP 1	MOPP 4
Desert L	< MOPP 4	-
Desert M	N.S.	-
Desert H	< MOPP 4	-
Tropic L	< MOPP 4	-
Tropic M	< MOPP 4	-
Tropic H	< MOPP 4	-

Climate	Desert	Tropic
MOPP 1 L	N.S.	-
MOPP 1 M	N.S.	-
MOPP 1 H	N.S.	-
MOPP 4 L	N.S.	-
MOPP 4 M	N.S.	-
MOPP 4 H	N.S.	-

ALL SIGNIFICANT DIFFERENCES READ ACROSS ROWS ONLY

CORE TEMPERATURE

Exercise Level	MOPP 1 L	MOPP 1 M	MOPP 1 H	MOPP 4 L	MOPP 4 M	MOPP 4 H
Desert	< M,H	< H	-	< M,H	< H	-
Tropic	< M,H	< H	-	< M,H	< H	-

MOPP Level	MOPP 1	MOPP 4
Desert L	< MOPP 4	-
Desert M	< MOPP 4	-
Desert H	< MOPP 4	-
Tropic L	< MOPP 4	-
Tropic M	< MOPP 4	-
Tropic H	< MOPP 4	-

Climate	Desert	Tropic
MOPP 1 L	N.S.	-
MOPP 1 M	> Tropic	-
MOPP 1 H	N.S.	-
MOPP 4 L	N.S.	-
MOPP 4 M	> Tropic	-
MOPP 4 H	N.S.	-

ALL SIGNIFICANT DIFFERENCES READ ACROSS ROWS ONLY

MEAN WEIGHTED SKIN TEMPERATURE

Exercise Level	MOPP 1 L	MOPP 1 M	MOPP 1 H	MOPP 4 L	MOPP 4 M	MOPP 4 H
Desert	< H	N.S.	-	< M,H	< H	-
Tropic	< M,H	< H	-	< M,H	< H	-

MOPP Level	MOPP 1	MOPP 4
Desert L	< MOPP 4	-
Desert M	< MOPP 4	-
Desert H	< MOPP 4	-
Tropic L	< MOPP 4	-
Tropic M	< MOPP 4	-
Tropic H	< MOPP 4	-

Climate	Desert	Tropic
MOPP 1 L	> Tropic	-
MOPP 1 M	> Tropic	-
MOPP 1 H	N.S.	-
MOPP 4 L	> Tropic	-
MOPP 4 M	> Tropic	-
MOPP 4 H	> Tropic	-

ALL SIGNIFICANT DIFFERENCES READ ACROSS ROWS ONLY

HEART RATE

Exercise Level	MOPP 1 L	MOPP 1 M	MOPP 1 H	MOPP 4 L	MOPP 4 M	MOPP 4 H
Desert	< M,H	< H	-	< M,H	< H	-
Tropic	< M,H	< H	-	< M,H	< H	-

MOPP Level	MOPP 1	MOPP 4
Desert L	< MOPP 4	-
Desert M	< MOPP 4	-
Desert H	< MOPP 4	-
Tropic L	< MOPP 4	-
Tropic M	< MOPP 4	-
Tropic H	< MOPP 4	-

Climate	Desert	Tropic
MOPP 1 L	N.S	-
MOPP 1 M	N.S	-
MOPP 1 H	N.S	-
MOPP 4 L	> Tropic	-
MOPP 4 M	N.S.	-
MOPP 4 H	N.S.	-

ALL SIGNIFICANT DIFFERENCES READ ACROSS ROWS ONLY

TOLERANCE TIME

Exercise Level	MOPP 1 L	MOPP 1 M	MOPP 1 H	MOPP 4 L	MOPP 4 M	MOPP 4 H
Desert	-	-	< L,M	-	< L	< L,M
Tropic	-	-	< L,M	-	< L	< L,M

MOPP Level	MOPP 1	MOPP 4
Desert L	> MOPP 4	-
Desert M	> MOPP 4	-
Desert H	> MOPP 4	-
Tropic L	N.S.	-
Tropic M	> MOPP 4	-
Tropic H	> MOPP 4	-

Climate	Desert	Tropic
MOPP 1 L	N.S	-
MOPP 1 M	N.S.	-
MOPP 1 H	N.S.	-
MOPP 4 L	N.S.	-
MOPP 4 M	< Tropic	-
MOPP 4 H	N.S.	-

ALL SIGNIFICANT DIFFERENCES READ ACROSS ROWS ONLY

APPENDIX C

The six graphs in Appendix C show the mean (±SD) subject core temperatures, mean weighted skin temperatures and heart rates of the subjects for each of the experimental test conditions.

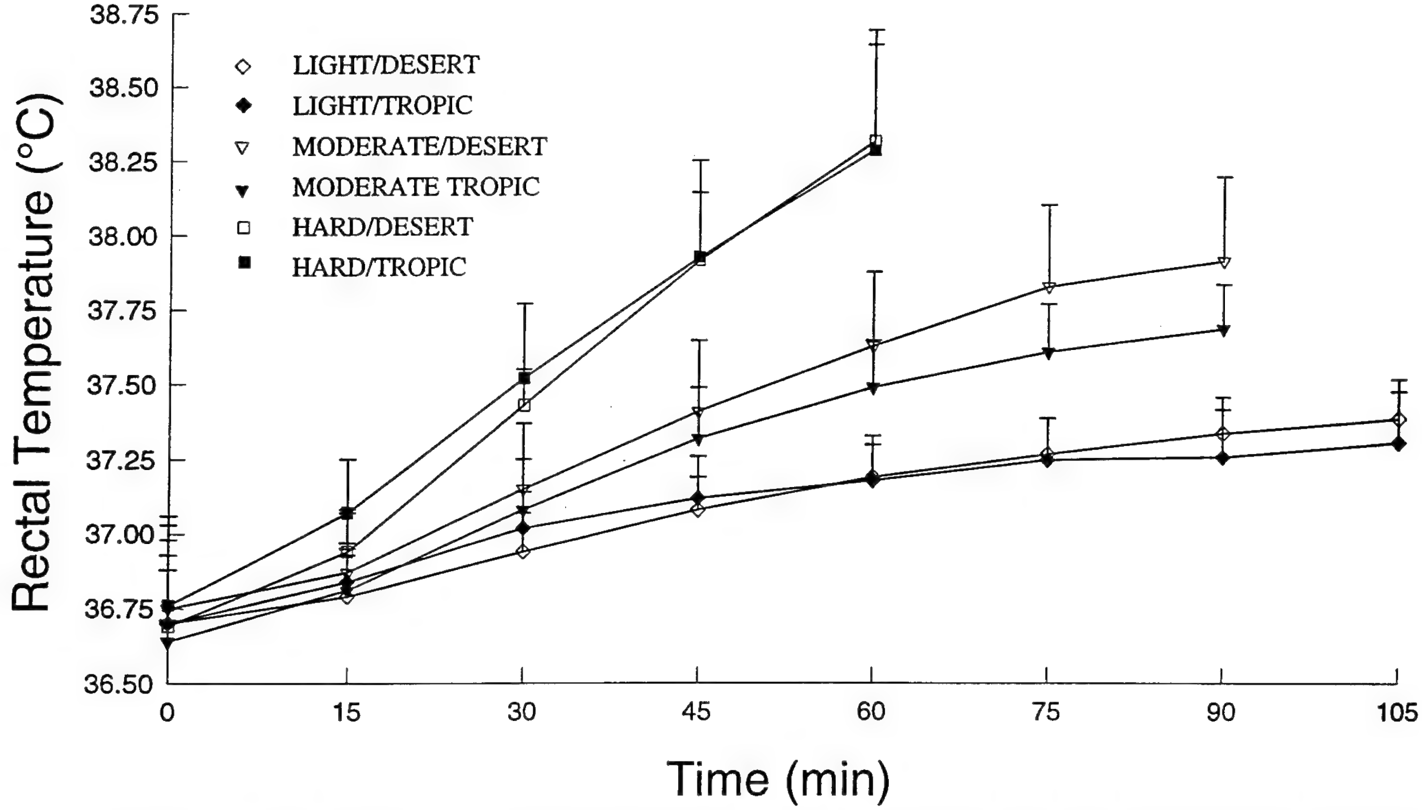

Figure 1C. The mean ±SD rectal temperature of the subjects at 15 minute intervals during all experiments in both desert and tropic climates in MOPP 1.

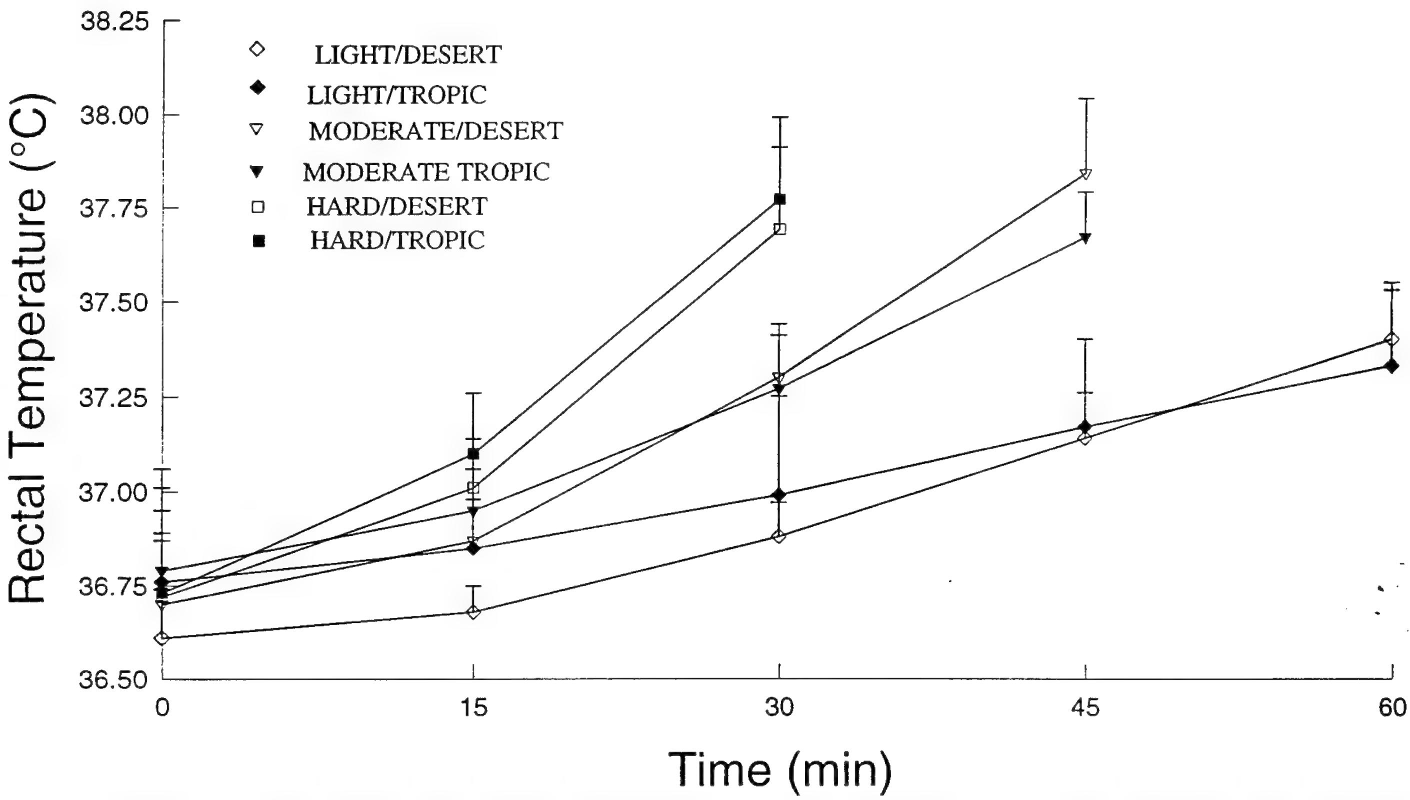

Figure 2C. The mean ±SD rectal temperature of the subjects at 15 minute intervals during all experiments in both desert and tropic climates in MOPP 4.

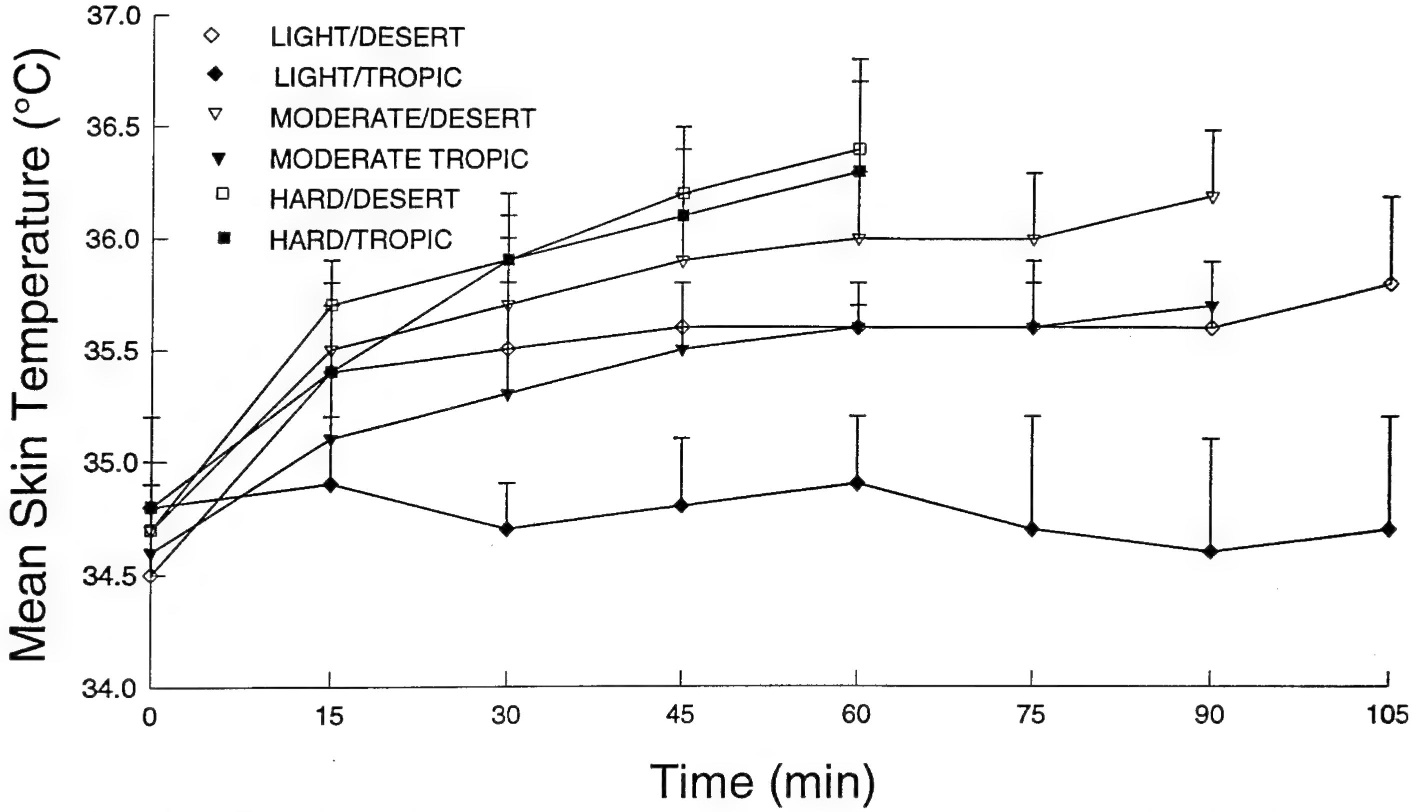

Figure 3C. The mean ±SD mean skin temperature of the subjects at 15 minute intervals during all experiments in both desert and tropic climates in MOPP 1.

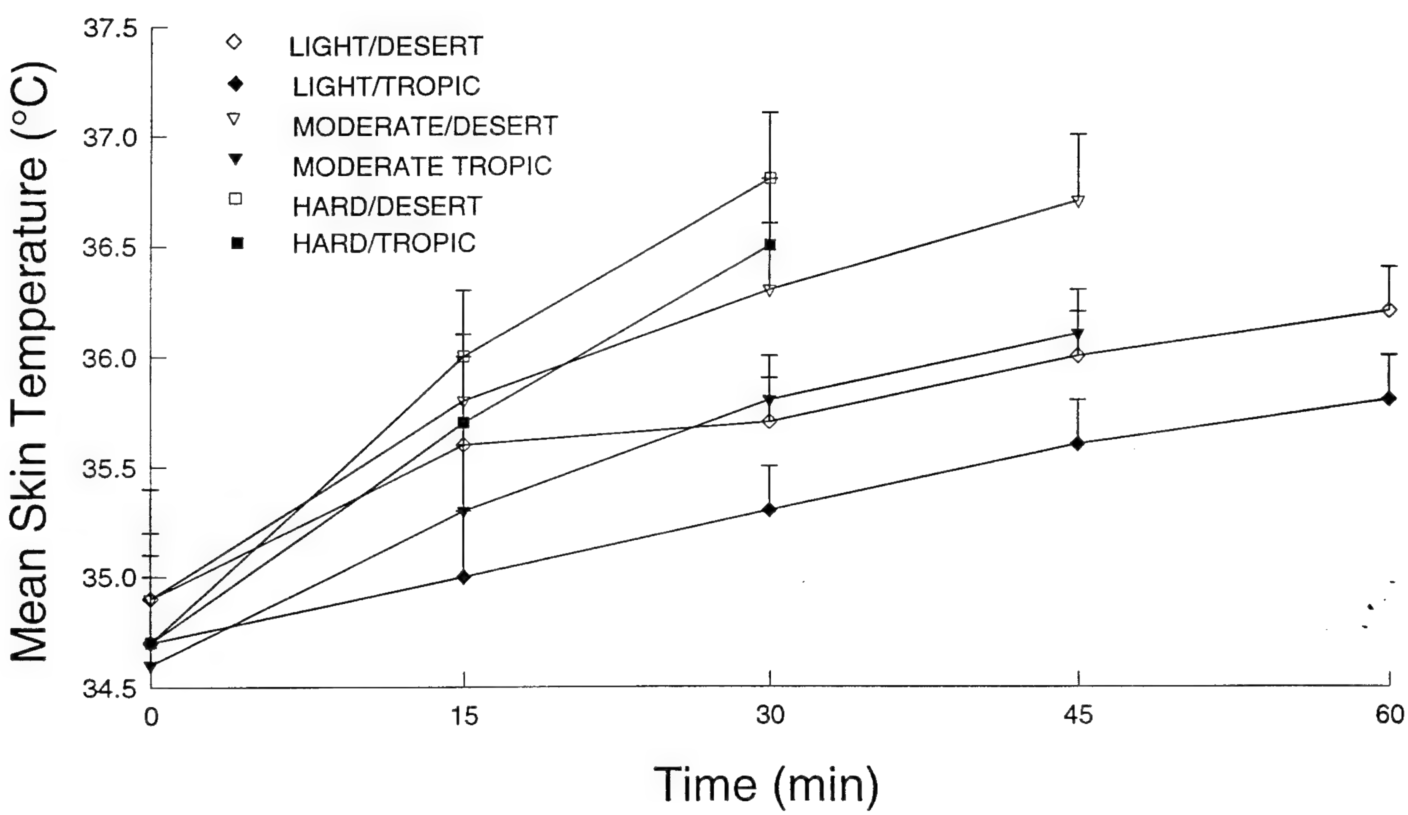

Figure 4C. The mean ±SD mean skin temperature of the subjects at 15 minute intervals during all experiments in both desert and tropic climates in MOPP 4.

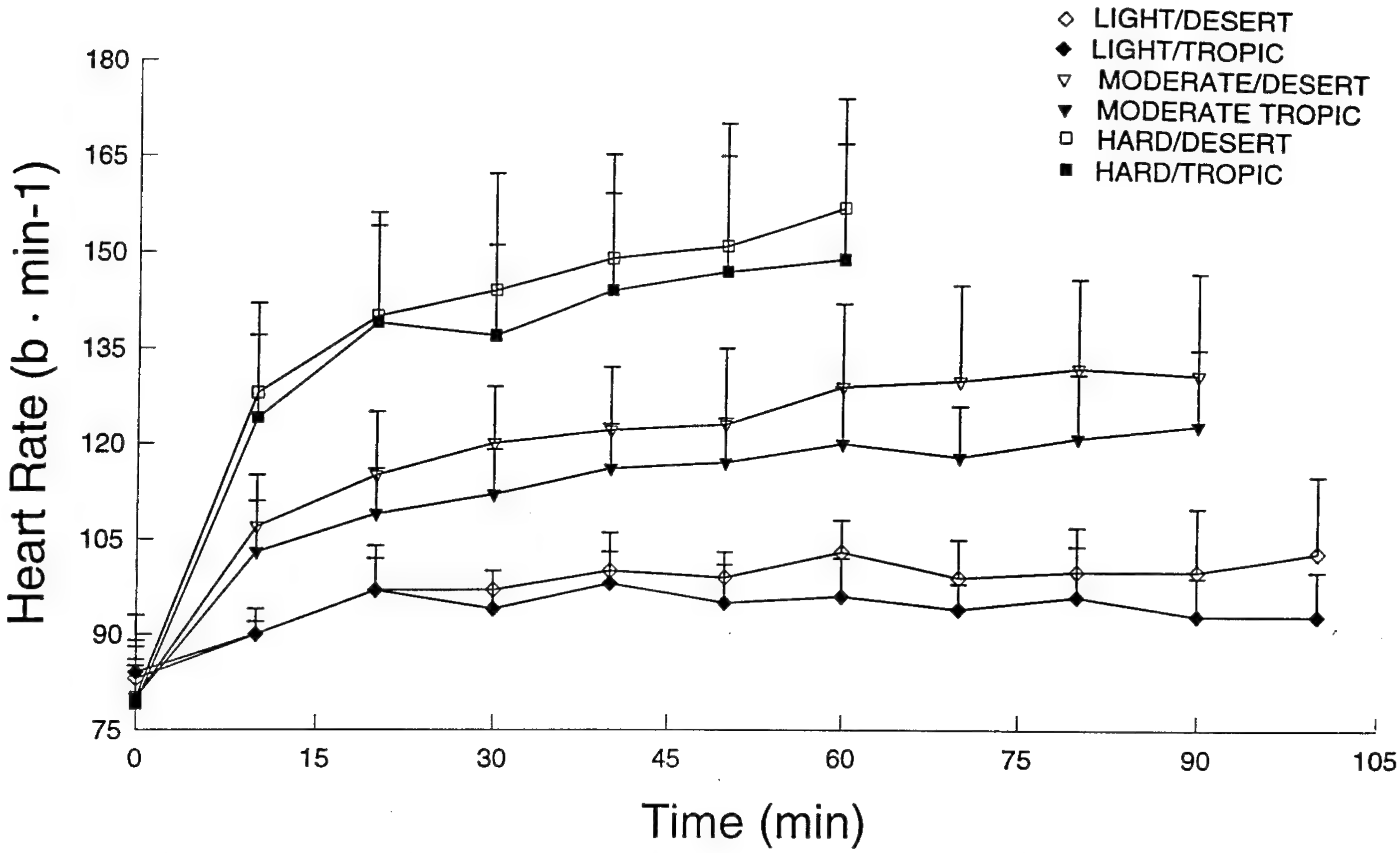

Figure 5C. The mean ±SD heart rate of the subjects at 10 minute intervals during all experiments in both desert and tropic climates in MOPP 1.

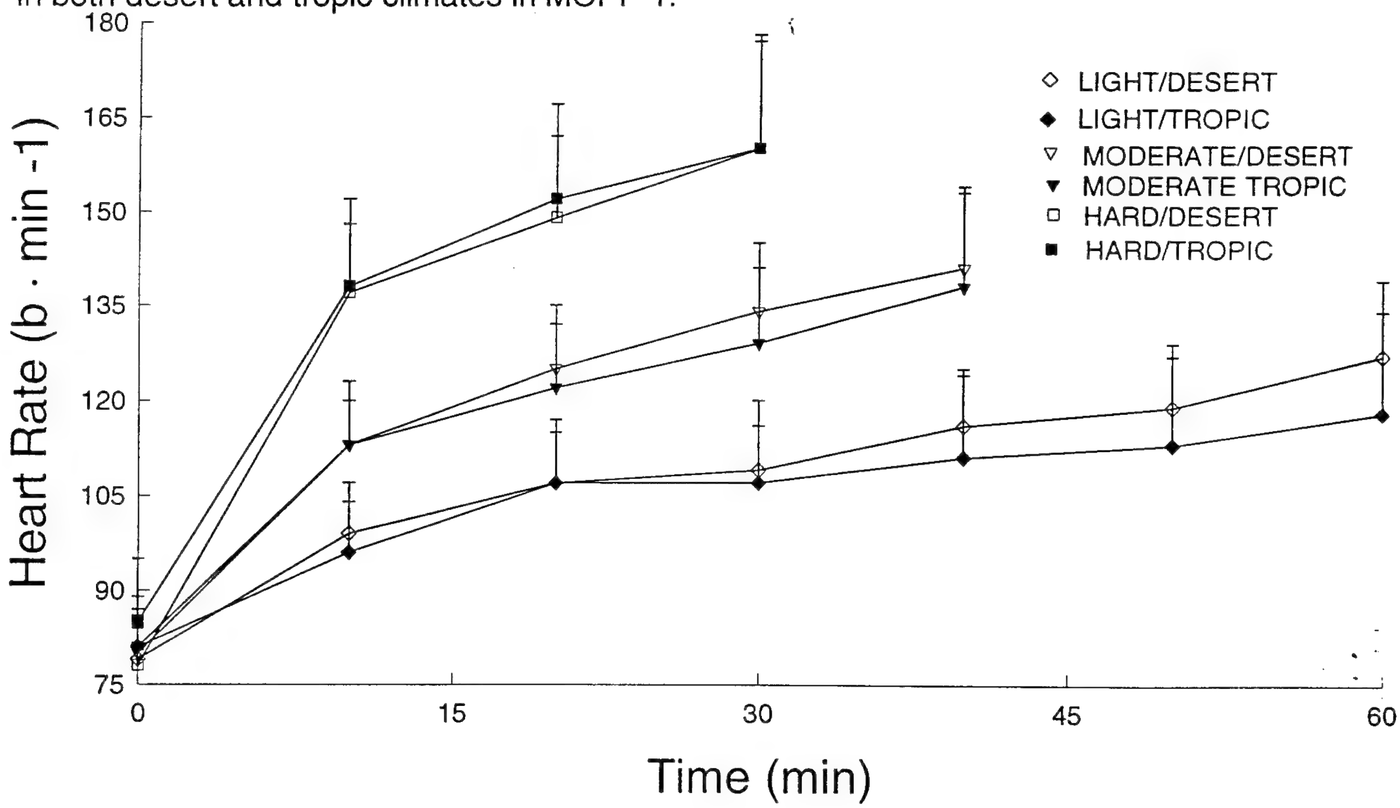

Figure 6C. The mean ±SD heart rate of the subjects at 10 minute intervals during all experiments in both desert and tropic climates in MOPP 4.

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